RC J0311+0507: A Candidate for Superpowerful Radio Galaxies in the Early Universe at Redshift z=4.514 *

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Abstract. A strong emission line at 6703Åhas been detected in the optical spectrum for the host galaxy (R=23.1) of the radio source RC J0311+0507 (4C+04.11). This radio galaxy, with a spectral index of 1.31 in the frequency range 365–4850 MHz, is one of the ultrasteep spectrum objects from the deep survey of a sky strip conducted with RATAN-600 in 1980–1981. We present arguments in favor of the identification of this line with Lyα at redshift $z = 4.514$. In this case, the object belongs to the group of extremely distant radio galaxies of ultrahigh radio luminosity ($P_{1400} = 1.3 \times 10^{29} WHz^{-1}$). Such power can be provided only by a fairly massive black hole ($\sim 10^9 M_\odot$) that formed in a time less than the age of the Universe at the observed z (1.3 Gyr) or had a primordial origin.

Key words: radio sources, radio galaxies, black holes

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1. Introduction

The radio source RC J0311+0507 (the RATAN Cold Catalog; Parijskij et al. 1991, 1992) was dis covered in 1980–1981 observations during the first deep survey of a sky strip with the RATAN-600 multifrequency complex (Berlin et al. 1981). The catalog included more than 1145 radio sources with a flux density limit higher than 10 mJy at 7.6 cm. The RATAN-600 observations at various azimuths allowed a positional accuracy of $\sim$15″to be obtained. This accuracy is not enough for deep optical identi- fications, but is quite sufficient for deep VLA observations. The absence of catalogs with an adequate sensitivity in those years made it difficult to identify them with known objects. The first catalog of a high positional accuracy with a sensitivity up to 200 mJy was the UTRAO (Texas) Catalog at $\sim$80 cm (Douglas et al. 1996). Douglas kindly provided us data on our surveyed area long before the publication of this catalog. This allowed us to identify at least the objects of the RC catalog with fairly steep spectra. There were about one-third of these sources. RC J0311+0507

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was one of them. Since its spectral index ($\sim \nu^{-\alpha}$) is $\alpha \approx 1.2$, it was included in the subsample of candidates for distant objects of the Big Trio Project (Goss et al. 1994; Kopylov et al. 1995; Parijskij et al. 1999; Verkhodanov et al. 2001).

Note that RC J0311+0507 is a fairly bright low-frequency radio source. It was first detected at a frequency of 85 MHz (Mills et al. 1958) and was then reliably recorded at 178 MHz (Gower et al. 1967) as the object 4C+04.11 with a flux density of 5.5 Jy. Röttgering et al. (1994) independently selected RC J0311+0507 to be included in their sample of objects with steep radio spectra (365B B0309+049). However, subsequently they did not study it in the optical range, possibly because of an uncertain spectral index. RC J0311+0507 also closely corresponds in its parameters to the objects of the sample of steep-spectrum radio sources by Tielens et al. (1979).

Analysis of this sample revealed the then most distant radio galaxy, 4C+41.17 (z=3.80, Chambers et al. 1990).

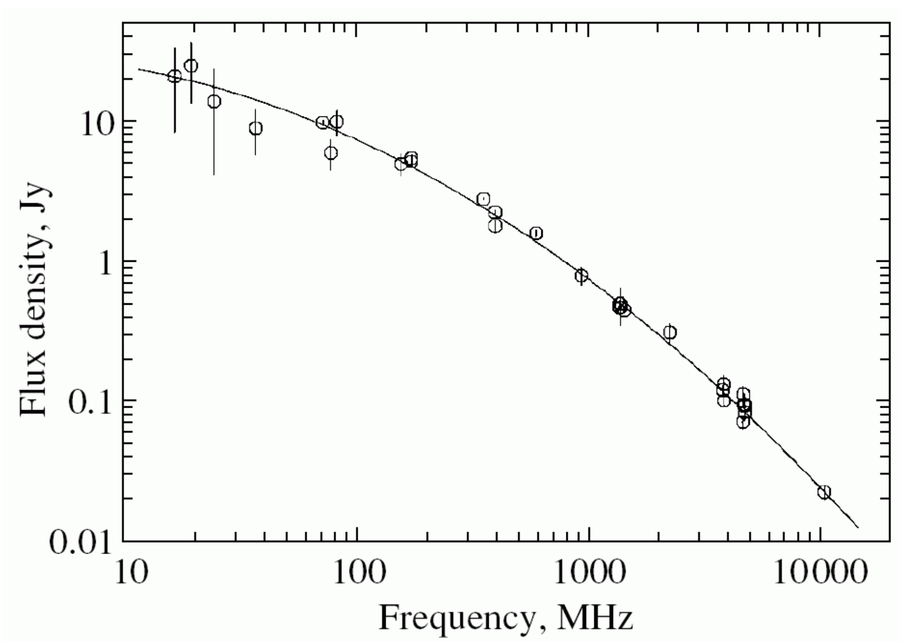

Figure 1: Radio spectrum of RC J0311+0507 constructed from the data accumulated by 2005. The spectral index in the frequency range 365-4850 MHz is 1.31. The spectrum flattening toward the low frequencies suggests that the components of the radio source are compact.

We have studied the object on VLA with a resolution of 1".4 at 21 cm as part of the Big Trio Project (RATAN–VLA–BTA). The radio source turned out to be compact, about 2", with an AD (Asymmetric Double) structure. The VLA archival data with a resolution of 0".4 at 6 cm show the presence of a third, very weak component of small angular size. Below, we provide the main data on this object, including the radio data and optical studies with the 6-m BTA telescope of the Special Astrophysical Observatory (SAO) (identification, multicolor photometry, and spectroscopy).

2. Observations

2.1. Radio Observations

Figure 1 shows the radio spectrum of RC J0311+0507 with all of the available measurements collected in the CATS database (Verkhodanov et al. 1997), including the RATAN-600 multifrequency data. We also added the measurements at 38 and 178 MHz from Williams et al. (1968). The curve

in Fig. 1 corresponds to the equation

$$\log S = 1.423 + 0.212 \log \nu - 0.241 (\log \nu)^2 (1)$$

that was obtained by fitting a parabola to all measurements (31 data points). In the frequency range 365–4850 MHz, the object has an ultrasteep spectrum (α=1.31), which is the first signature of a high redshift. The increase in the spectral slope from low to high frequencies is also a characteristic property of distant compact powerful radio sources.

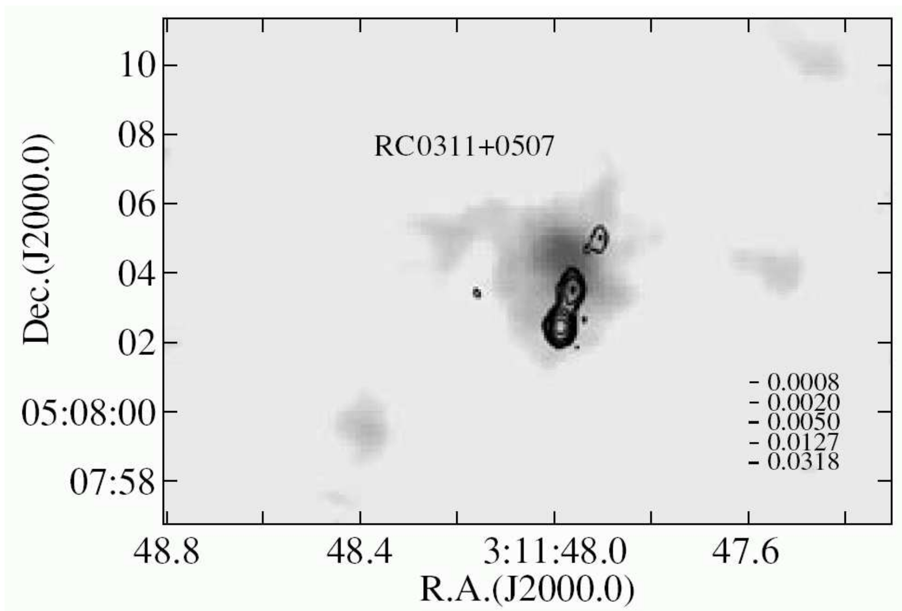

Figure 2: Superposition of the 4860 MHz VLA isophotal image of the radio source RC J0311+0507 obtained in 1985 on the R-band BTA 1995 image of the host galaxy.

The VLA observations carried out by W.M. Goss in June 1995 with a resolution of 1".4 at 1425 MHz provided evidence for a compact two-component structure (Parijskij et al. 1996). Based on their VLA observations with a similar resolution, Rottgering et al. (1994) determined the radio source as an extended one with a size of 1".6. With the kind permission of B. Burke, we found the image of this object obtained by J. Hewitt in 1985 at 4860 MHz with a resolution of 0".4 in the VLA archive where a linear triplet structure with a total angular size of 2".8 is seen. Based on these data, we can classify RC J0311+0507 as a compact steep-spectrum (CSS) object. It is distinguished by a large flux density asymmetry (~20 times) between the two extreme components, which is much more commonly observed in quasars than in radio galaxies.

2.2. Optical Identification

Based on the direct BTA image with an exposure time of 400 s at 2" seeing obtained in September 1995 with a 580×520 ISD015 CCD array (pixel size 0".205×0".154), we identified the radio source (Parijskij et al. 1996) with a faint galaxy (R≈22.9 in a 5" aperture). The optical-to-radio luminosity ratio turned out to be the standard one for the population of luminous radio galaxies (McCarthy 1993; Parijskij et al. 1996). Figure 2 shows the optical object with the superimposed VLA 4860 MHz isophotes.

2.3. Multicolor Photometry

In November 1999, we performed the next observations with the PMCCD instrument (a TX1024A array with 0".206×0".206 pixels). We obtained B, V, R, and I images with exposure times of 600, 1000, 400, and 1000 s, respectively, at ∼2" seeing. The photometric measurements with a 5" aperture corrected for the extinction in the Galaxy (A_B=0.83, A_V=0.64, A_R=0.51, and A_I=0.37) yielded magnitudes of >24.9, 24.8±0.6, 22.6±0.15, and 22.3±0.4, respectively. The color characteristics are close to those expected for massive galaxies at $z = 3 - 5$, and the complete absence of the object in the B band does not contradict to the emission cutoff beyond the Lyman 912 Ålimit. The R-band size of the galaxy slightly exceeds its I-band size. This may suggest the presence of a hydrogen halo around the host galaxy that is commonly observed in distant radio galaxies. The presence of a halo can lead to a considerable increase in the object's size if the strong Lyα line falls not far from the passband maximum of the corresponding filter (see, e.g., RC J0105+0501; Soboleva et al. 2000), where the Lyα line increases significantly the V-band size of the object).

2.4. Spectroscopic Observations

In September and November 2004, we obtained BTA spectra of the host galaxy. The observations were carried out with the SCORPIO universal focal reducer that was put into operation on BTA late in 2003 as the main multipurpose, high-efficiency instrument (Afanasiev and Moiseev 2005). On November 8–9, 2004, we were able to obtain the best-quality spectrum of the host galaxy with a total exposure time of 3600 s in long-slit observations at 1" seeing. The gr300G grating provided the entire spectral range accessible to the instrument (3800–9400 Å) with a resolution of ∼20 Å, which is commonly used to study objects of this type. The slit width was 1" and the position angle was −11°. The spectrum was reduced using the SCORPIO data reduction and analysis software package (Afanasiev and Moiseev 2005) and is shown in Fig. 3. The size of the region of integration over the slit height was 1".6. The absolute spectrum calibration was performed using the spectrophotometric standard Hiltner 600 and is given in units of 10^{-17} erg cm^{-2} s^{-1}Å^{-1}.

An intense line is seen at a wavelength of 6703 Å. The line flux is ≈5×10^{-16}erg cm^{-2}s^{-1}, the $FWHM$ is ∼1500 km s^{-1}, and the equivalent width is ∼1000 Å. We interpret it as Lyα with a redshift of 4.514±0.001. The luminosity in this line is close to the (R-band) continuum luminosity, which is observed in steep-spectrum radio galaxies only for the Lyα line (McCarthy 1993).

The alternative interpretation ([O II] 3727 Åwith $z = 0.8$) is highly unlikely because of the complete absence of [O III] 5007 Å, which is usually twice as intense as [O II] 3727 Åfor this population of objects. The identification with Lyα is consistent with the weakness of other lines falling into the spectral range studied of which only the C IV 1549 Åline is detected with a signal-to-noise ratio of ∼2 at 10% of the Lyα intensity.

The ratio of the continuum levels in 400 Å–wide intervals on both sides of Lyα is ∼3. The lowering of the continuum at wavelengths shortward of Lyα is attributable to the absorption by the Lyα forest and is in agreement with the data for quasars at $z = 4.5$(Songaila 2004). In general, the spectrum of RC J0311+0507 is similar in its characteristics to the spectra of high-redshift radio galaxies (see, e.g., 8C 1435+63, $z = 4.261$, Fig. 1 in Spinrad et al. (1995)).

3. Discussion

Although $z = 4.514$ is considerably lower than the limiting redshifts detected to date, for galaxies (Malhotra and Rhoads 2005; Stanway et al. 2003; Pello et al. 2004) and quasars (Fan et al. 2003; Walter et al. 2004), RC J0311+0507 is only the second luminous radio galaxy detected at a redshift higher than 4.5.

Let us compare the main parameters of RC J0311+0507 with those of other radio galaxies at

$z > 4$. Only seven such galaxies are known and almost all of them have been studied more or less adequately. Table 1 successively lists the names of the radio galaxies, their redshifts, optical R (or I) magnitudes, infrared K magnitudes, 1400-MHz flux densities (NVSS; Condon et al. 1998) (except the object VLA J123642+621331, for which the data were taken from Richards (2000)), two-frequency spectral indices α from the Texas Survey (365 MHz) and NVSS (with the exception of VLA J123642+621331, for which only 1.4 and 8.5 GHz measurements are available; Richards 2000), the largest angular sizes (LAS) in arcseconds, and morphology of the radio galaxies in the standard notation (S–single, D–double, AD–asymmetric double, C–core, and E–extended). The last column gives references to the publications from which the redshifts, optical magnitudes, infrared magnitudes, and LAS of the radio sources were taken.

In three cases (VLA J123642+621331, TN J1123–2154, and 7C 1814+670), only a weak Lyα line was detected; in the remaining cases, the Lyα line is very intense. The color data (after the subtraction of the Lyα contribution, $\sim 0\overset{\text{m}}{.}7$) are consistent with new models for evolution of large galaxies.

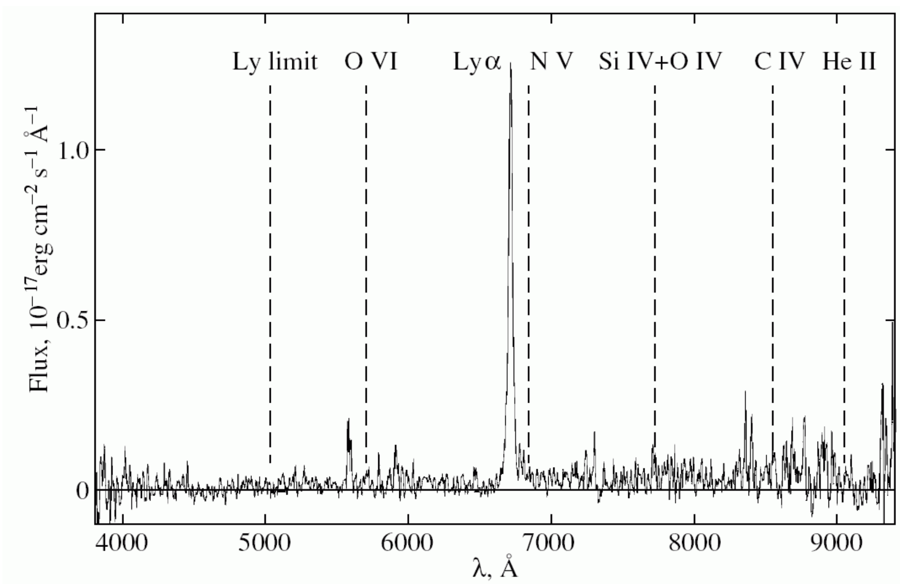

Figure 3: Optical spectrum of the host galaxy of the radio source RC J0311+0507. We identify a narrow, intense line at the center. with Lyα 1216 Å. The dashed indicate the expected positions of the emission lines typical of distant radio galaxies. Other spectral features include the residual effect of strong atmospheric lines after the subtraction of the night-sky spectrum.

Thus, for example, for the GALEV2 model (Bicker et al. 2004) with the assumed epoch of primary star formation ($z = 5$), the expected colors of the stellar population of an elliptical galaxy are given in Table 2.

This table once again confirms that the case with a high redshift is correct. In its redshift, RC J0311+0507 is second only to the object TN J0924–2201 ($z = 5.199$), but this source exceeds it in radio luminosity. Having determined the flux density 3.5 Jy at 254 MHz (which corresponds to the emission frequency 1400 MHz at $z = 4.514$) using interpolation over the spectrum, we obtain the power of the radio source, 1.3×10^{29} W Hz^{-1} (for H_0=70 km s^{-1}Mpc^{-1}, Ω_M=0.3, and Ω_Λ=0.7). RC J0311+0507 and 8C 1435+63 turn out to be similar in their parameters to superpowerful radio galaxies at $z > 4$, which exceed in luminosity Cyg A, the most powerful nearby radio galaxy, by a factor of $\sim$10.

An ultrahigh radio luminosity is a signature of a supermassive black hole ($M_{bh} \sim 10^9 M_\odot$) at the center of the host galaxy. However, in the standard model, the time scale of its growth from

the time of secondary ionization from $\sim 10M_{\odot}$ to $M_{bh} \sim 10^9 M_{\odot}$ is only ~0.5 Gyr. Therefore, the object can be of interest in connection with the problem of age crisis (Cunha and Santos 2004; Loeb and Barcana 2001). Not all of the models for the formation of supermassive black holes admit such a fast growth of their masses from several solar masses to $10^9 M_{\odot}$; either severe con straints on the rate of their growth are needed or one must accept the version of primordial (pregalactic) large black holes forming stellar systems around themselves that have been often discussed in recent years.

The weakness of other lines in the spectrum (Fig. 3) suggests that the main emission in the Lyα line is attributable to a halo that is poorly enriched with He II (1640 Å) and C IV (1549 Å). The upper limit on He II and C IV obtained by Dawson et al. (2004) for distant Lyα-emitting galaxies is 15% (our value is 10%). Therefore, we believe that their conclusion about the primordial nature of the hydrogen gas halo not enriched with nuclear reactions in stars of the host galaxy or population III stars ($z > 10-30$) (Loeb and Barcana 2001) for this object is also applicable to RC J0311+0507.

4. Conclusions

The goal of this paper is to draw the attention of astronomers that are interested in objects of the early Universe to the source RC J0311+0507.

With expanding capabilities of the BTA optical facilities and with refinement of the selection criteria by taking into account the international experience, increasingly distant objects from the sample of steep-spectrum RC objects can be studied.

Table 1: Data for radio galaxies at $z > 4$

Name	z	m_{opt}	mK	S_{1400},mJy	α	LAS	Morphology	References*:
TN J0924-2201	5.199	>24 R	21.7	71	1.65	1".2	D	1,2,2,3
RC J0311+0507	4.514	23.1 R	...	500	1.29	2.8	AD+C	4,4,–,4
VLA J123642+621331	4.424	24.9 I	21.4	0.5	0.94	0.4	C+E	5,5,5,6
6C 0140+326	4.413	24 I	20.0	91	1.17	2.6	D	7,8,9,8
8C 1435+63	4.261	23.6 I	19.5	497	1.37	3.9	D+C	10,10,9,11
TN J1338-1941	4.11	22.4 R	20.0	121	1.33	5.5	AD+C	7,12,12,13
TN J1123-2154	4.109	>24.5 R	20.3	49	1.57	0.8	S	7,2,2,3
7C 1814+670	4.05	24.1 R	19.4	236	1.08	18.	D	14,14,15,14

References: 1–Venemans et al. (2004), 2–De Breuck et al. (2002), 3–De Breuck et al. (2000), 4–this work, 5–Waddington et al. (1999), 6–Muxlow et al. (2005), 7–De Breuck et al. (2001), 8–Rawlings et al. (1996), 9–van Breugel et al. (1998), 10–Spinrad et al. (1995), 11–Lacy et al. (1994), 12–De Breuck et al. (2004), 13–De Breuck et al. (1999), 14–Lacy et al. (1999), 15–Lacy et al. (2000). RATAN–600 surveys deeper than previous ones have been used to prepare lists of a weaker population of ultrasteep-spectrum radio sources and we hope to advance further along the redshift scale.

Table 2: Observations and the GALEV2 model

Band	RC J0311+0507	Model $z = 4.5$	Model $z = 0.8$
B	>24.9	>28.84	23.86
V	24.8±0.6	24.30	22.64
R	23.3±0.3	23.19	21.71
I	22.3±0.4	22.23	20.28
K	...	20.87	17.30

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References

V. L. Afanasiev and A. V. Moiseev, Pisma Astron. Zh. 31, 214 (2005) [Astron. Lett. 31, 194 (2005)].
A. B. Berlin, E. V. Burlaenko, V. Ya. Golnev, et al., Pisma Astron. Zh. 7, 290 (1981).
J. Bicker, U. Fritze, V. Alvensleben, et al., Astron. Astrophys. 413, 37 (2004).
K. C. Chambers, G. K. Miley, and W. J. M. van Breugel, Astrophys. J. 363, 21 (1990).
J. J. Condon, W. D. Cotton, E. W. Greisen, et al., Astron. J. 115, 1693 (1998).
J. V. Cunha and R. Santos, Int. J. Mod. Phys. D 13, 1321 (2004).
S. Dawson, J. E. Rhoads, S. Malhotra, et al., Astrophys. J. 617, 707 (2004).
C. De Breuck, W. van Breugel, D. Minitti, et al., Astron. Astrophys. 352, L51 (1999).
C. De Breuck, F. Bertoldi, C. Carilli, et al., Astron. Astrophys. 424, 1 (2004).
C. De Breuck, W. van Breugel, H. J. A. Rottgering, and G. Miley, Astron. Astrophys., Suppl. Ser. 143, 303 (2000).
C. De Breuck, W. van Breugel, H. Rottgering, et al., Astron. J. 121, 1241 (2001).
C. De Breuck, W. van Breugel, S. A. Stanford, et al., Astron. J. 123, 637 (2002).
J. N. Douglas, F. N. Bash, and F. A. Bazyan, Astron. J. 111, 1945 (1996).
X. Fan, M. A. Strauss, and D. P. Schneider, Astron. J. 125, 1649 (2003).
W. M. Goss, Yu.N.Parijskij, A.I. Kopylov, et al., Turk. J. Phys. 18, 894 (1994).
J. F. R. Gower, P.F.Scott, and D.Wills, Mon. Not. R. Astron. Soc. 71, 49 (1967).
A. I. Kopylov, V. M. Goss, Yu. N. Pariiskii, et al., Astron. Zh. 72, 613 (1995) [Astron. Rep. 39, 543 (1995)].
M. Lacy,A.J.Bunker, andS.E.Ridgway,Astron. J. 120, 68 (2000).
M. Lacy, G. Miley, S. Rawlings, et al., Mon. Not. R. Astron. Soc. 271, 504 (1994).
M. Lacy, S. Rawlings, G. J. Hill, et al., Mon. Not. R. Astron. Soc. 308, 1096 (1999).
A. Loeb and R. Barcana, Ann. Rev. Astron. Astrophys. 39, 19 (2001).
S. Malhotra and J. E. Rhoads, Astrophys. J. 626, 666 (2005).
P. J. McCarthy, Ann. Rev. Astron. Astrophys. 31, 639 (1993).
B. Y. Mills, O. B. Slee, and E. R. Hill, Aust. J. Phys. 11, 360 (1958).
T. W. B. Muxlow, A. M. S. Richards, S. T. Garrington, et al., Mon. Not. R. Astron. Soc. 358, 1159 (2005).
Yu. N. Parijskij, N. N. Bursov, N. M. Lipovka, et al., Astron. Astrophys., Suppl. Ser. 87, 1 (1991).
Yu. N. Parijskij, N. N. Bursov, N. M. Lipovka, et al., Astron. Astrophys., Suppl. Ser. 96, 583 (1992).
Yu. N. Parijskij, W. N. Goss, A. I. Kopylov, et al., Bull. Spec.Astrophys.Obs. 40, 5 (1996).
Yu. N. Parijskij, W. N. Goss, A. I. Kopylov, et al., Astron. Astrophys. Trans. 18, 437 (1999).
R. Pello, D. Shaerer, J. Richard, et al., Astron. Astrophys. 416, L35 (2004).
S. Rawlings, M. Lacy, K. M. Blundell, et al., Nature 383, 502 (1996).
E. A. Richards, Astrophys. J. 533, 611 (2000).
H. J. A. Röttgering, M. Lacy, G. R. Miley, et al., Astron. Astrophys., Suppl. Ser. 108, 79 (1994).
N. S. Soboleva, O. V. Verkhodanov, et al., Pisma Astron. Zh. 26, 723 (2000) [Astron. Lett. 26, 623 (2000)].
A. Songaila, Astron. J. 127, 2598 (2004).
H. Spinrad, A. Dey, andJ.R.Graham, Astrophys.J. 438, L51 (1995).
E. R. Stanway, A. J. Bunker, and R. G. McMachon, Mon. Not. R. Astron. Soc. 342, 439 (2003).
A. G. G. M. Tielens, G. K. Miley, and A. G. Willis, Astron. Astrophys., Suppl. Ser. 35, 153 (1979).
W. G. M. van Breugel, S. A. Stanford, H. Spinrad, et al., Astrophys. J. 502, 614 (1998).
B. P. Venemans, H. J. A. Rottgering, R. A. Overzier, et al., Astron. Astrophys. 424, L17 (2004).
O. V. Verkhodanov, Yu.N.Parijskij, N.S.Soboleva, et al., Bull. Spec. Astrophys. Obs. 52, 5 (2001).

O. V. Verkhodanov, S. A. Trushkin, H. Andernach, and V.N. Chernenkov, Astron.Soc.Pac.Conf. Ser. 125, 322 (1997).

I. Waddington, R. A. Windhorst, S. H. Cohen, et al., Astrophys. J. 526, L77 (1999).

F. Walter, C. Carilli, and F. Bertoldi, Astrophys. J. 615, L17 (2004).

P. J. S. Williams, R. A. Collins, J. L. Caswell, and D. J. Holden, Mon. Not. R. Astron. Soc. 139, 289 (1968).

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